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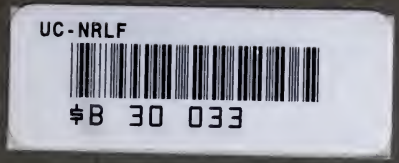

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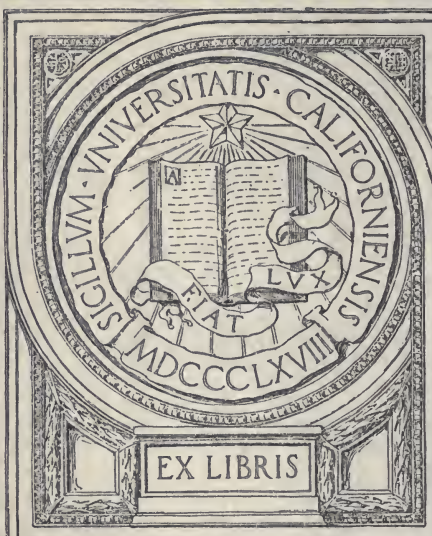

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BULLETIN No. 3.

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH.

ADVISORY COUNCIL.

A STUDY ON THE PERFORMANCE OF "NIGHT-GLASSES."

BY

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PREFATORY NOTE.

The Department of Technical Optics of the Imperial College of Science and Technology, South Kensington, in which the work described in this Bulletin has been carried out, was established in 1917, and is supported by grants from the Board of Education, the London County Council, and the Department of Scientific and Industrial Research.

It is thought that the results obtained will be of interest and value, particularly to makers of telescopes and night-glasses for marine use. Accordingly the Advisory Council for Scientific and Industrial Research have decided that the report shall be published and thus be made available for manufacturers and others who may be interested.

Department of Scientific and
Industrial Research,
15, Great George Street,
Westminster, S.W.1.

March 1919.

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ANNOTATED

INTRODUCTION.

THE investigation set out in the following pages was carried out for the Department of Scientific and Industrial Research by the Technical Optics Department of the Imperial College of Science and Technology, South Kensington, by Mr. L. C. Martin, D.I.C., A.R.C.S., B.Sc., Lecturer. A few introductory words may not be out of place.

The war has made many extraordinary and exacting demands upon the optician. Not the least of these has been the problem of producing efficient night-glasses, *i.e.*, telescopes specially designed for the observation of objects in a feeble light, as, for example, during sniping operations in the morning and evening. It is generally known that a pair of ordinary Galilean field-glasses enables objects to be seen at night which are invisible to the naked eye—not because of smallness of size, but solely because of insufficiency of light.

Up to a certain limit increase in the magnifying power of a telescope results in increased visibility, but when the power is so great that the emergent pencils from object-points no longer fill the pupil of the eye of the observer, then the conditions are altered and a point is reached beyond which vision falls off with increase of magnifying power, because of the diminishing brightness of the picture produced on the retina. The practical problem which Mr. Martin, therefore, set out to solve was this:—For a given size of telescope O.G. and given light conditions what magnifying power should be used to give the best results so far as visibility is concerned?

Assuming, as Mr. Martin does, that the pupil of the eye in the dusk has a diameter of about 8 mm., it is evident that, so long as the magnifying power is not greater than the ratio of the diameter of the O.G. and the diameter of the pupil, the brightness of the retinal picture is practically the same no matter what the magnifying power may be; but as soon as this limit is exceeded and the magnifying power made greater than this ratio, then the brightness of the retinal picture falls off with increase of magnifying power. In spite, however, of this falling off in brightness increased visibility still results, within limits, from increased magnifying power. The problem of the night-glass therefore practically resolves itself into the determination of the extent to which, under given light conditions, magnifying power may be put into a telescope at the expense of the reduction of the effective diameter of the pupil, and the consequent reduction of the brightness of the retinal picture.

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Imperial College of Science and Technology,
South Kensington.

A STUDY ON THE PERFORMANCE OF "NIGHT-GLASSES."

UNTIL comparatively recent times the subject of vision under faint illumination had been little studied, and the action of certain types of telescopes in giving enhanced visibility at night (in spite of the fact that the brightness of an image can never exceed that of the object and in spite of reflection and absorption in the instrument) was regarded as unexplained. It will be remembered that Herschel described the power of his reflecting telescope to render visible the hands on a church clock in the darkness when the church itself was invisible to the naked eye. Certain investigations, however, as to the minimum brightness perceptible have shed some light on the subject, for it seems clear that in the end we shall be alone concerned with the retinal image, its definition, size, and brightness, and the sensitiveness of the eye. Given similar conditions as far as these factors are concerned, there would appear no reason to doubt that the visibility of an image would be independent of the particular optical means by which it is produced.

Previous Investigations.—The general results of the previous investigations may be reviewed with advantage. All workers agree that the minimum intrinsic brightness necessary for the perception of an object varies greatly with its size. With the same surface brightness a small area will cease to be visible before a larger one when the illumination of each is reduced equally. It has been established also that the fovea, which is the place of greatest possible visual acuity on the retina, and which subtends about one degree at the principal point of the eye, is not in most persons the region which is most sensitive to light, although the opposite is sometimes the case. In night-vision the eye wanders from point to point, and in striving to catch a glimpse of some object will frequently be more successful when the line of ordinary vision is a few degrees away. Therefore, in most of the experimental work to be described in this paper, no attempt was made to limit the observations to any special retinal region, as was done by certain previous workers.

For the fovea, Loeser* found that the threshold brightness varied inversely as the square of the diameter of the source (or inversely as the area). Abney's first experiments† indicated that the threshold varies inversely as $D^{1\cdot65}$, where D is the diameter of the source; Abney and Watson in a later paper‡ find that the power of D concerned is 1 for the fovea, and for discs, therefore, which do not subtend an angle of more than about 1°; but at 5° from the fovea the threshold varies inversely as the diameter for a subtense of the object between about 1° 8′

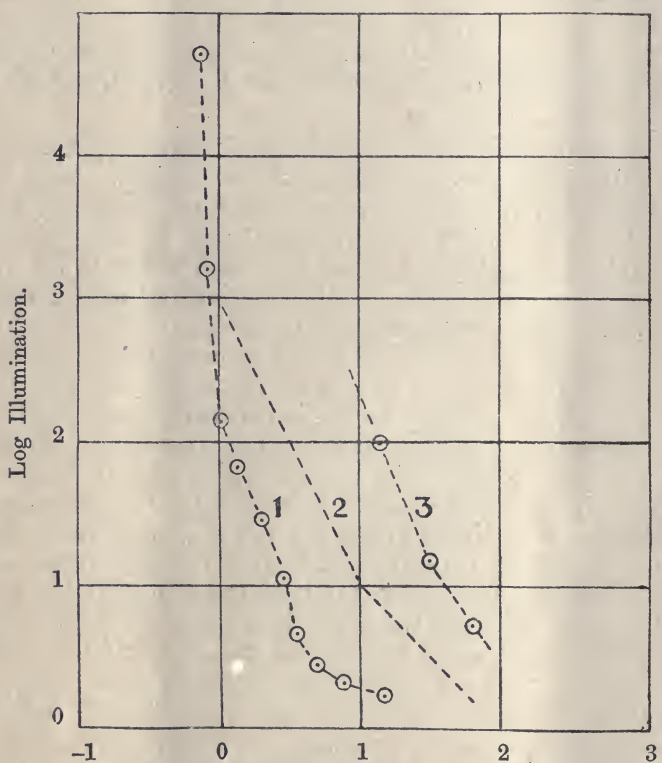
* Helmholtz, "Physiol. Optik." 3rd Edn., 2, p. 284.
† Abney, "Phil. Trans. Roy. Soc.," A. 190 (1897), pp. 155–195.
‡ Abney and Watson, "Phil Trans. Roy. Soc.," A. 216, p. 891.

and 34′, and inversely as the square of the diameter for a subtense between about 34′ and 17′. These results appear to contradict those of Loeser.

Apart from experiments solely concerned with the absolute limit of vision, certain tests requiring a definite visual acuity, or some standard visibility, are of interest.

The work of Druault* on visual acuity under decreasing illumination provides some interesting data. This work was performed by illuminating a Snellen test chart (with letters of varying size) by a source of which the distance could be varied. The intensity of illumination necessary to read each line of type was thus found. From the results the angular subtense of the width of the marks forming the letters can be compared with the illumination necessary to read them. The results are plotted in Figure 1.

FIG. 1.



Log angular subtense of object in minutes.

Typical results of previous observers.

(1) Druault.
(2) Paterson and Dudding.
(3) Abney and Watson.

N.B.—Ordinates are not from the same origin in the three "curves" above.

* Tscherning, "Optique Physiol.," p. 260.

Paterson and Dudding* have also given results bearing on a similar problem. In this case the object viewed was made of equal visibility to a standard comparison object; intensity of illumination and angular subtense were found, but the exact nature of the test-object is not clear, as only the one angular dimension is given.

Brightness of an Image.—Let E be the diameter of the entrance pupil of the telescopic system, and let M be the magnification, then.

$$\text{Diameter of exit-pupil} = \frac{E}{M}.$$

In the case of terrestrial telescopes, prismatic binoculars, and various other instruments the exit-pupil is coincident with the pupil of the eye.

Let I be the intrinsic brightness of the object; then, while the exit-pupil is larger than the eye-pupil the intrinsic brightness of the retinal image will be equal to Ik, where k is dependent on absorption and reflection; when, however, the exit-pupil is smaller than the eye-pupil the brightness of the retinal image will be proportional to

$$Ik.\left(\frac{E}{M}\right)^2 \frac{1}{d^2},$$

where d is the diameter of the eye-pupil. The product will be proportional to M^{-2} when the other factors are constant. We neglect possible spherical aberration for the present. In certain instruments, the Galilean binocular for example, the illumination of the image will not be cut down in this manner, as the exit-pupil and eye-pupil do not coincide in use.

We may at once deduce from the results given above that, while the exit-pupil is larger than the pupil of the eye we shall continuously derive advantage by increasing the magnification, since the size of the image increases while its brightness is constant. At a certain point, however, if a constant entrance-pupil is used, the illumination will begin to be reduced. These effects, of course, are already well known.

If without a telescope the threshold brightness for an object subtending an angle α be T, then

$$T \propto \frac{1}{\alpha^n} \text{ say.....(1).}$$

When using the telescope we assume the illumination of the image proportional to M^{-2}, but the subtense of the image is αM; therefore if T' be the threshold brightness of the object *when using the telescope,*

$$T' \propto \frac{M^2}{(\alpha M)^n}$$

or $T' \propto M^{2-n}$ for a constant object.

---

* *Illuminating Engineer*, May, 1915.

The first experimental work on this subject has been to determine the value of the index n in particular cases by naked eye methods. If the value found is greater than 2 an improvement in visibility may be expected when using a telescope by increasing the magnification even when the exit-pupil is smaller than that of the eye, and *vice versâ*.

Plotting the logarithms of light intensity as ordinates and logarithms of angular subtense as abscissæ, the slope of the curve indicates the power of the diameter to which the necessary illumination is inversely proportional since

$$\log(T^{-1}) = \text{const.} + n \log a \quad (2).$$

The reduced results of Abney and Watson, Druault, and Paterson and Dudding are thus treated for purposes of comparison, but it must be remembered that intensity of illumination has not been given in the same units. Therefore the slopes only of the curves for similar abscissæ should be compared. Also a different criterion of "visibility" has been adopted in each case. A common characteristic is a change of slope from roughly "2" for a small angular subtense to about 1 for a large subtense. Druault appears to find this at about 6 minutes of arc (subtense of the thickness of the mark forming a letter), Paterson and Dudding at 10 minutes, while the work of Abney and Watson indicates its existence between 31 and 62 minutes. These results cannot be condemned *à priori* as contradictory owing to the different conditions of experiment. It will be at once apparent that they have a most important bearing on the performance of telescopes under low illuminations. It appeared desirable, however, to repeat and extend some of these experiments under more exact conditions and thus to obtain more definite material for the interpretation of the action of telescopes.

Any aberrations of the eye will undoubtedly enter into the question. If present, they may affect definition when an instrument having a large exit pupil is employed.

Experimental Precautions.—A few considerations as to experimental methods and precautions may be given.

Adaptation to darkness is the chief difficulty in the work. Experiments were made at first under the impression that the increase in sensitiveness would be complete in something like 15 minutes, but it was quickly apparent from threshold values taken on the same object that adaptation was in evidence for an hour at least, especially if the general field of view was at all illuminated.

Blanchard* has since published results confirming these observations. We note that in his curve connecting log. threshold

* *Phys. Review*, XI., Feb. 1918, p. 94.

and time the slope is nearly uniform between 30 and 60 minutes, the threshold falling from log = 5·9 to log = 6·1. According to Blanchard the sensibility is rising for several hours. In order that experimental results might be kept free from vitiation due to this cause as far as possible, series of results were always repeated in the reverse order, the mean values being taken.

In order to determine how nearly the results obtained with telescopes can be co-related with the effects of unaided vision some experiments were made with a small white clock-dial of cardboard and a black pointer; this was viewed with a telescope having a number of eyepieces of varying powers, and also with the naked eye, the distance from the dial being varied in the latter case to imitate the effect of varying magnification.

The dial was illuminated by a Nernst lamp taking a regulated current of ·3 ampere in order to obtain a steady luminosity. The light could be reduced by means of "neutral" screens and a rotating sector of the Lummer-Brodhun type.

Experiments with Telescopes.—Using a constant object-glass with a series of eyepieces both magnification and illumination of the retinal image may vary. The instrument (which was a small one) was set up for the proper working distance as used in the experiments, and magnifying power and diameter of exit-pupil were carefully measured for each eyepiece. Assuming a value of 8 mm. for the diameter of the pupil of the observer's eye, and allowing for the loss of light at each air to glass surface in the system, the relative luminosity of the image on the retina in each case may be calculated. Also the angular subtense of the retinal image at the nodal point of the eye may be determined. The method of experiment was to increase the sector aperture till the "time" on the dial could be read: the mean of several results for the necessary sector aperture was found in each case.

For the naked eye the effective illumination on the dial was ·052 metre candles with the sector at an aperture of 1·0.* The effective illumination with each eyepiece is thus calculated in terms of metre candles and is tabulated with the angular subtense of the breadth of the image of the pointer (*see* Table I.).

Naked Eye Experiments.—In these experiments the sector was run at constant apertures and several observers found the distance at which the pointer became distinguishable. A series of results was taken with decreasing illumination and the tests were then repeated with increasing light, the mean of the two results being taken in each case. Effective illumination and the angular subtense of the breadth of the pointer are thus determined (*see* Table II.).

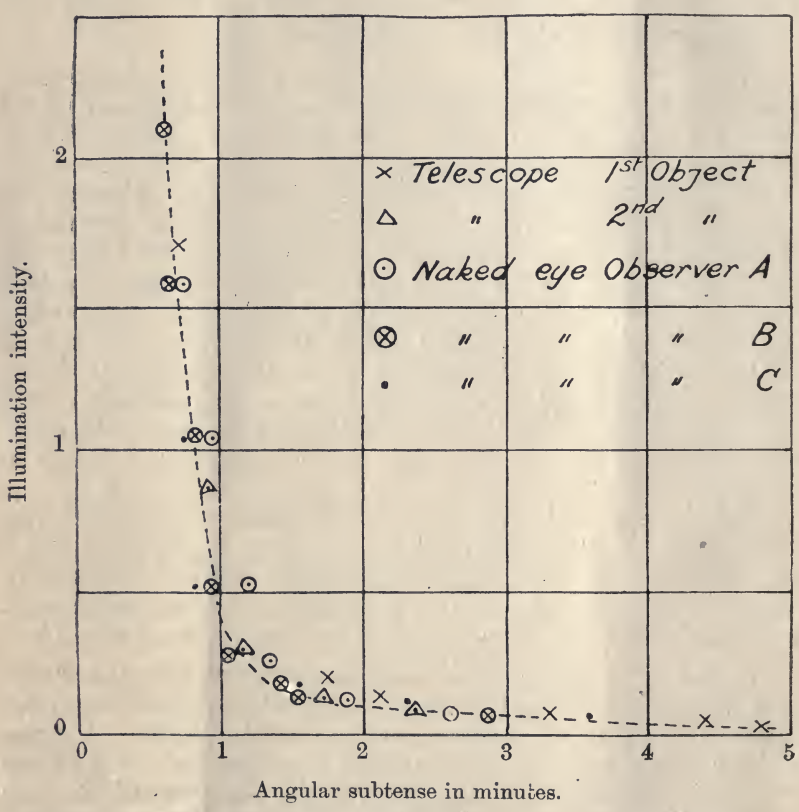
Throughout this work three or four separate readings are generally made by an observer at one point. Then, as the same point is taken on the return, each result quoted is the

* Aperture 50·0 corresponds to 90°.

mean of six or eight readings. In work of this kind no single reading may be trusted.

Comparison of results obtained (*see* Fig. 2) with and without the telescope shows a fairly close co-relation, but the agreement could not be expected to be very exact owing to the uncertain difference between monocular vision with the telescope and binocular vision in the naked eye tests, also to the uncertainty of the assumption as to the size of the pupil. Nevertheless the experiments fulfilled their purpose in showing that consistent results could be obtained by naked eye methods which can be applied to the problem in question.

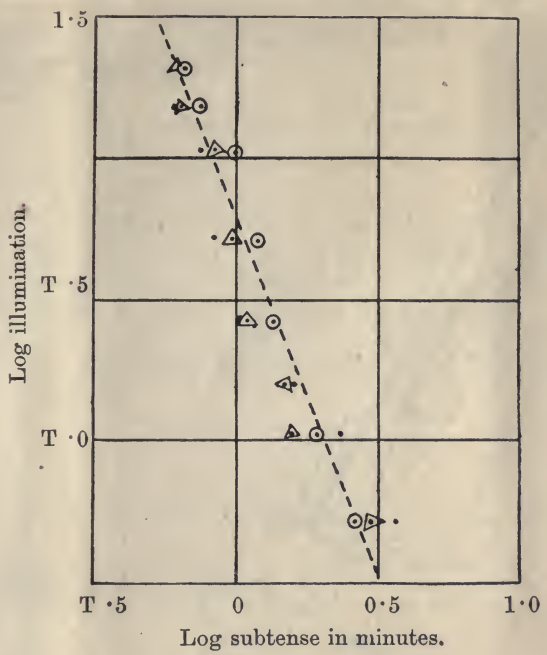
FIG. 2.



To seek the law connecting the results of the naked eye tests it is convenient to plot logarithms of angular subtense against logs of illumination necessary at the limit of vision. From the *slope* of the resulting curve or line the required relation can be obtained. In this case the illumination necessary to perceive the pointer is inversely proportional to the angular

subtense raised to the power 2·6 (Fig. 2A), taking an approximation for the results of the three observers.

FIG. 2A.

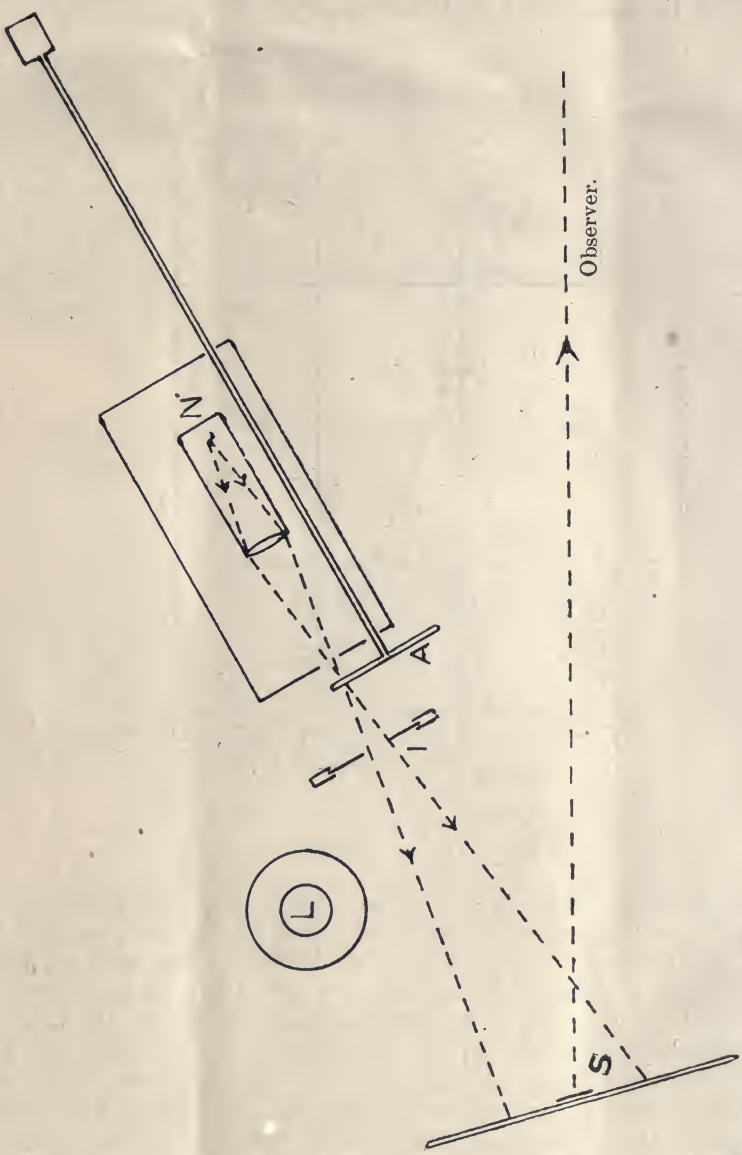


VISIBILITY OF WHITE DISC.

Naked Eye Methods.—Further preliminary experiments by naked eye methods were made on small white discs against a dark background. The sector proved inconvenient as a method of varying the illumination, and use was made of an annulus similar to that employed by Sir W. Abney,* to whom the author is indebted for the loan of the instrument. A diagram is given of the complete apparatus, Fig. 3. The Nernst lamp, taking a regulated current, is mounted inside a light-tight box. An image of the filament is formed at a narrow aperture, immediately in front of which the annulus is placed. Two additional neutral-tinted screens of platinised glass were employed further to dim the light when necessary. The annulus is controlled by a thin shaft passing through the back of the box, which could be extended to any desired length. This arrangement worked excellently as a variable source of light, and has been employed throughout these experiments. The intensity could be varied in the ratio 1 to 2,000 approximately.

* Abney, "Proc. Roy. Soc.," A. 190 (1897).

FIG. 3.



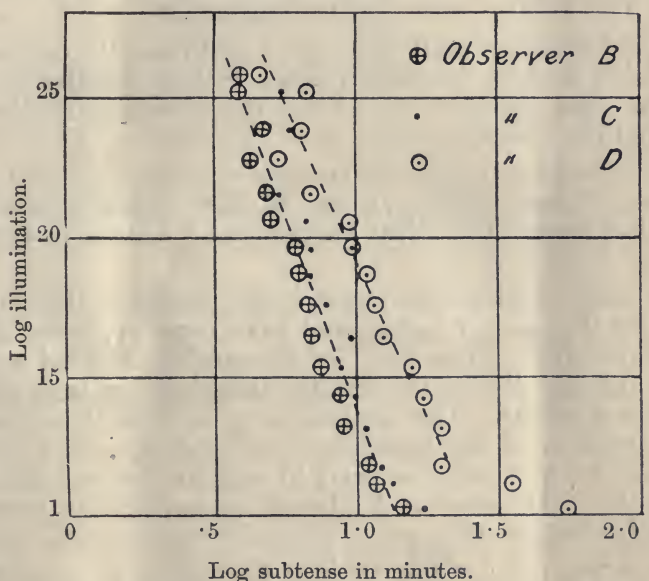
The calibration of the annulus was performed very carefully by two observers separately against a Lummer-Brodhun sector, and the transmission of each auxiliary screen was found with great care. The whole apparatus is used inside a completely darkened room.

In making these preliminary experiments observers were kept in complete darkness for about 15 minutes. They then observed the illuminated disc and were asked to move away from it till the limit of visibility was reached; they were,

however, to be sure they could just see it. All observers found the outer parts of the retina more sensitive, and considerable practice is necessary before anyone can establish a kind of standard visibility which can be taken as the limit. The disc may appear to flicker or only to appear at intervals. Vision is disturbed also by luminous sensations which prevent the perception of the object. Nevertheless after a little experience the limit is very well marked and exceedingly consistent results can be obtained (*see* Table III.). Distances of the eye from the object were found in the darkness by means of a knotted cord. Readings were deemed trustworthy (*see* above) after about 20–30 minutes in darkness.

These results are plotted in the Diagram, Fig. 4. All the observers were somewhat new to this class of work, especially D, who could only be satisfied with foveal fixation and has therefore higher threshold values. The general "slope" of the lines appears to be about 2·5 or 2·6, but the work revealed the necessity of extending the observations to greater values of angular subtense.

FIG. 4.



MEASUREMENT OF INTENSITY OF ILLUMINATION.

This work was not concerned with the accurate measurement of absolute threshold illuminations, but rather with relative values. Nevertheless an approximate measurement was made by comparison with a Hefner Standard. For an equivalent

sector opening of 1, which means 1 per cent. of the full illumination, the illumination on the surface was found to be ·05 metre candle.

In the preliminary experiments just described a disc of white card was used as the object. This is somewhat objectionable as for threshold values the power of the source has to be so far reduced that it may be comparable with any stray or reflected light. The use of black matt paper on a background of black velvet obviates this difficulty and suitable discs can be easily cut from it. A comparatively bright source can then be employed.

A photometric measurement showed that

$$\frac{\text{Reflecting power of black paper}}{\text{Reflecting power of magnesium oxide}} = \frac{2 \cdot 35}{100}.$$

Abney and Watson give the reflecting power of magnesium oxide as 0·83, which indicates that the reflecting power of the paper surface is 0·019.

A similar measurement for the black velvet gives its reflecting power as ·0018.

For an equivalent sector value of 1, therefore, one square centimetre of the paper surface radiates normally with a power of $3 \times 10-8$ candles, assuming the cosine law.

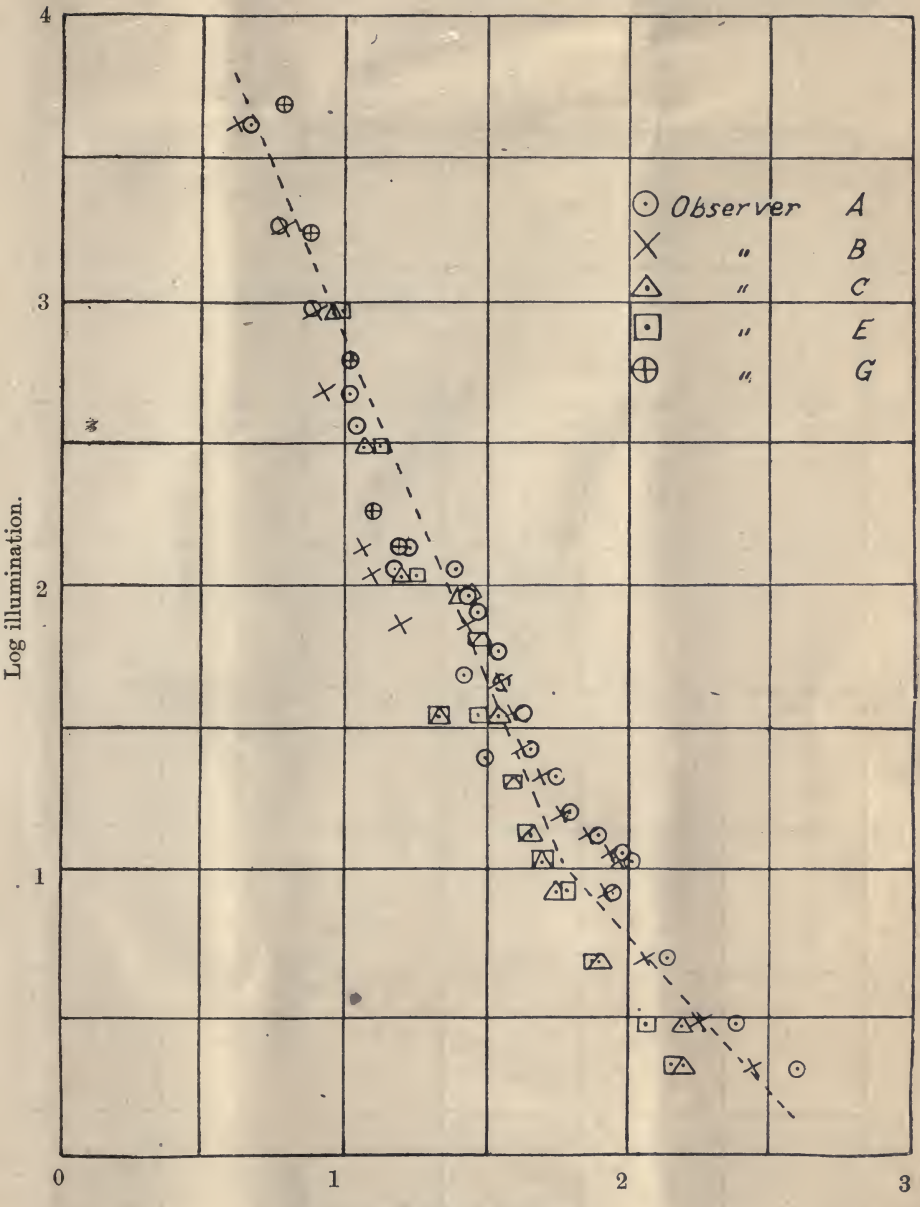
In the following results the log of 100 times the equivalent sector value has been plotted in order to keep positive characteristics. The energy received by the eye can readily be calculated if required.

An extended series of observations was now made, with the assistance of observers B, C, E, and G, on the visibility of black paper discs against the velvet background. Results in Table 4 and Figs. 5 and 6.

The results obtained show that, in the first place, the angular area of the illuminated background has a considerable influence on the visibility of the disc, for the method adopted was to change to larger discs with a greater distance in order to extend the series of results. This resulted in a proportional diminution of the subtense of the background in relation to the object, which for every observer appears to cause a distinct break in the results. The values of A, plotted separately, illustrate this very well. *See* Fig. 6.

The second point of interest is in the change of slope of the "lines" at log subtense = 1·8 nearly. This was found by all who worked in this region. Below this subtense the tangent of the angle of slope is about 2·4 for the general results, but the discontinuity of the results with a change of relative size of "field" masks the true value of the slope, which rises to about 3 in results obtained with one background and disc only for some observers. For higher values of angular subtense the slope becomes about 1 or rather more.

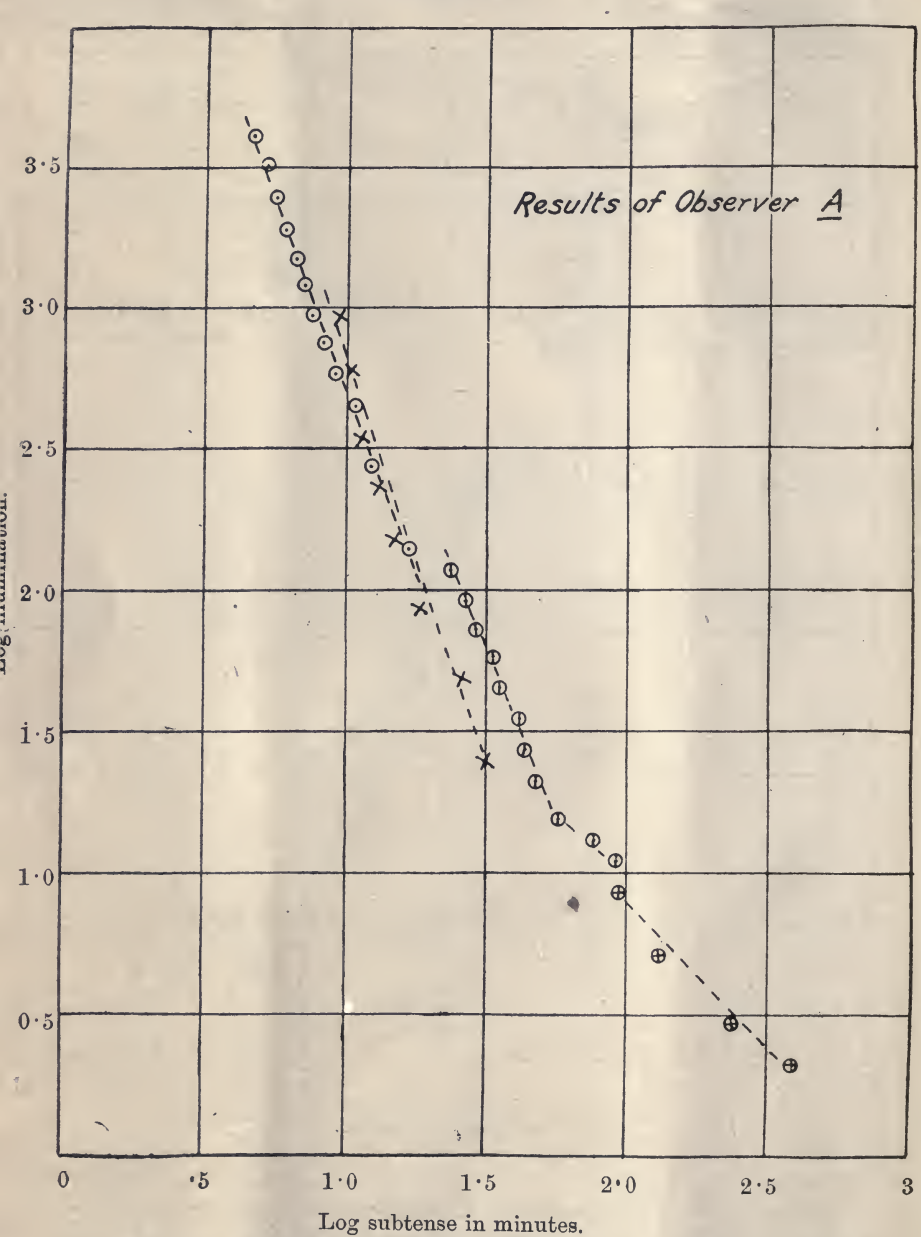
FIG. 5.



It was judged of importance to verify these results by working with a constant distance and constant size of background. It was found quite as easy to obtain limiting values of illumination by enabling the observer to rotate the annulus till the disc finally disappears. Auxiliary screens could be placed in position if

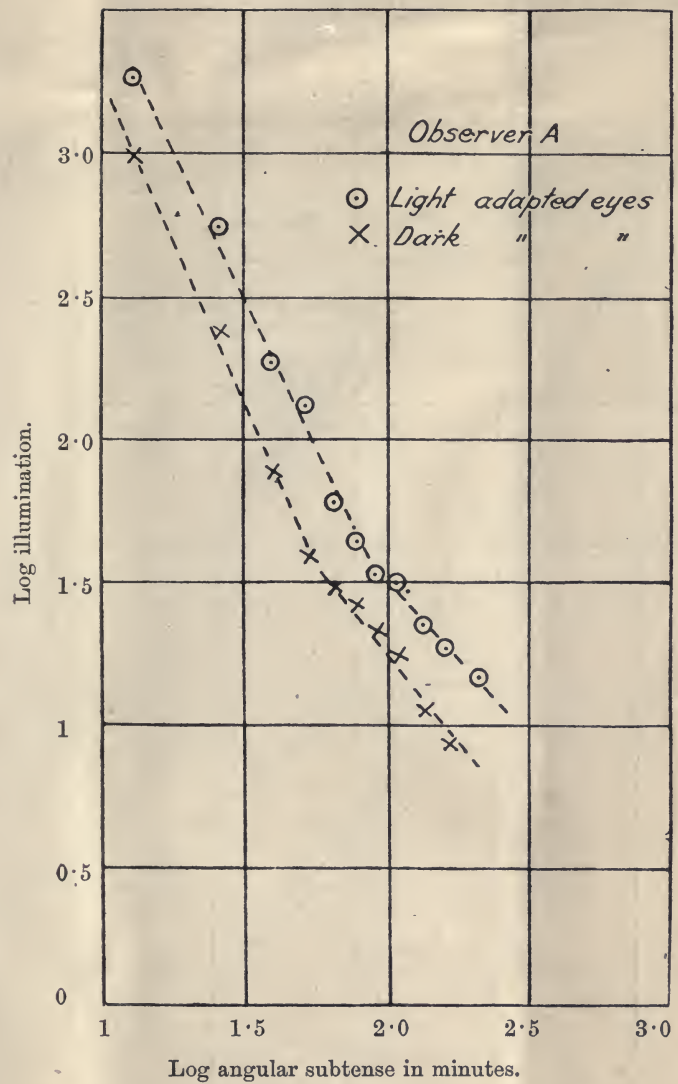
necessary as before. A series of squares was employed, cut from the same black paper, and placed successively against the black velvet background.

FIG. 6.



The results obtained are given in Table 5, diagrams 8, 9, 10.

FIG. 8.



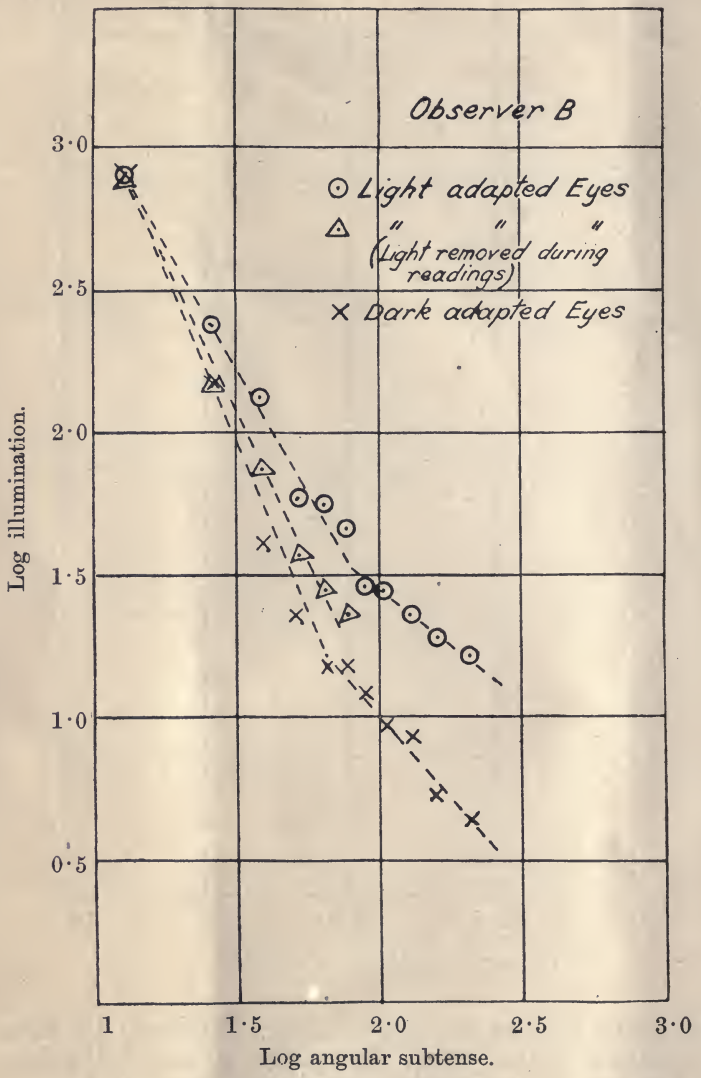
These values confirm the results already obtained ; the same sudden change of slope occurs, the average change being from about 2·5 to a value apparently somewhat greater than 1.

In these results the scale of illumination is slightly altered ; for equivalent sector value 1 the illumination on the disc = ·015 metre candle.

A further extension of the previous work appeared desirable to determine the effect with a "dead black" background, when the value will be dependent on the true threshold of vision and not on the contrast effect between a small area of comparatively

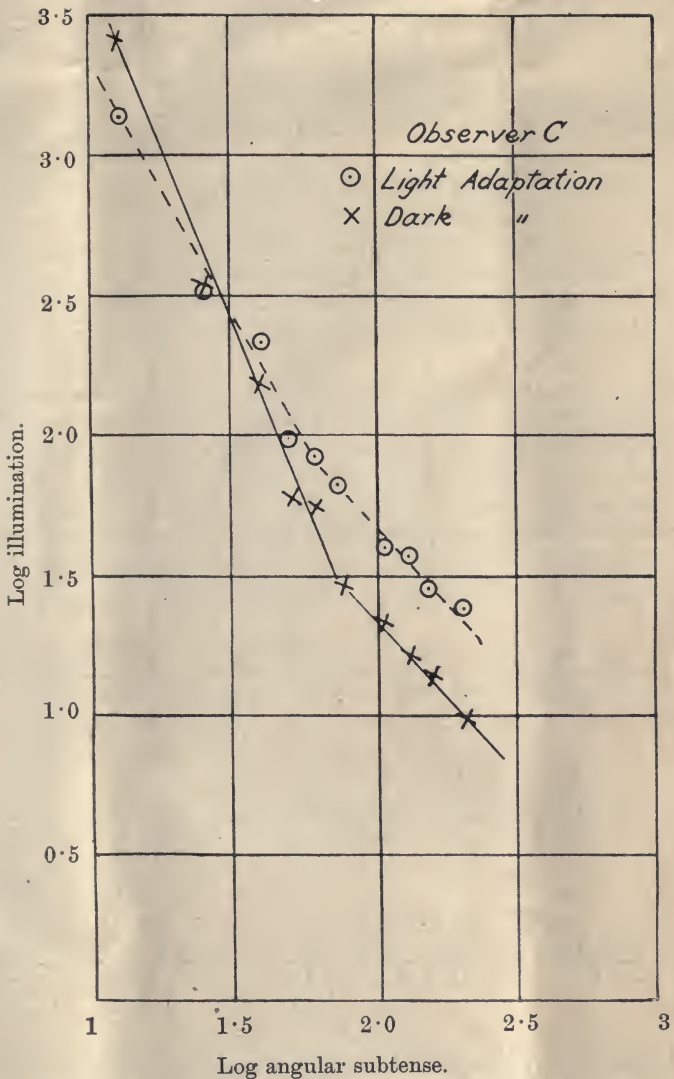
great intrinsic brightness and a large one of much lesser brightness, which however might still be easily seen when the small area has ceased to be recognisable.

FIG. 9.



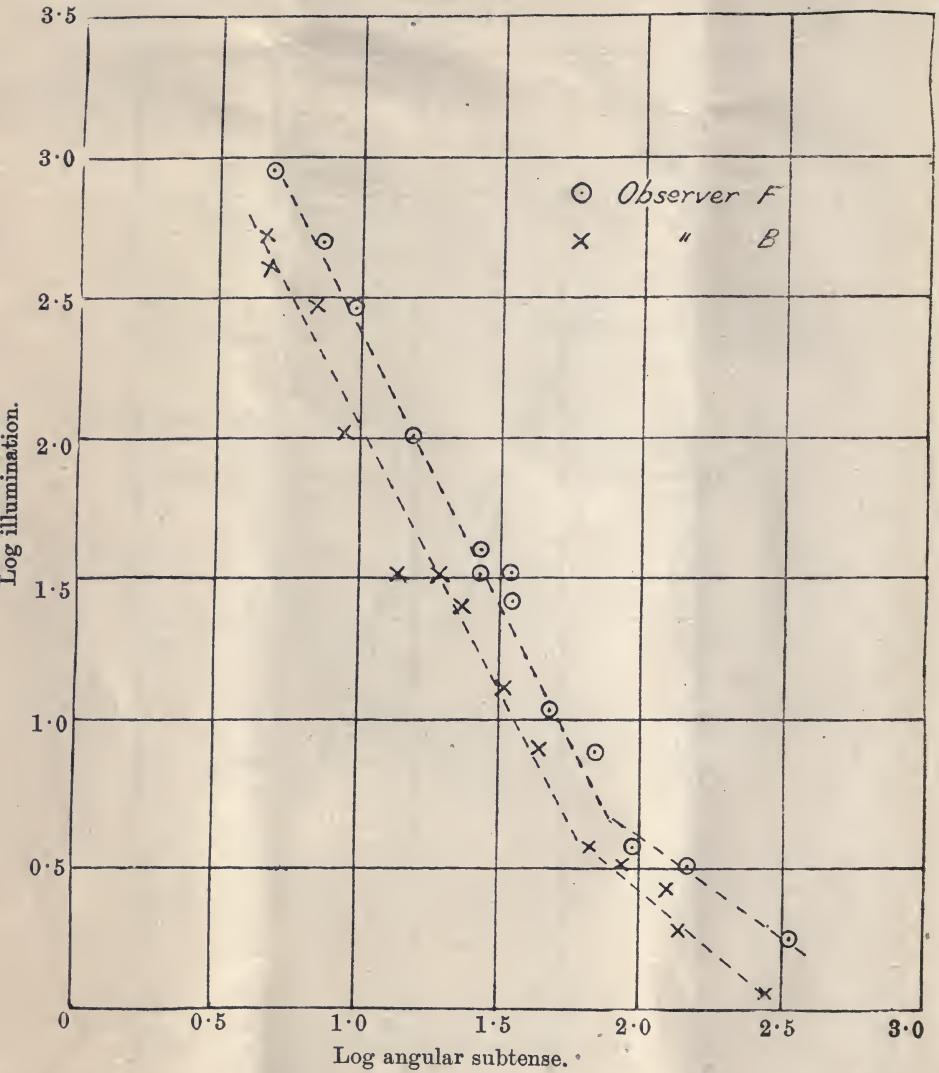
Visibility of Objects against a dead black Background.—We can see, however, that the object and background may be such that at a certain point the latter ceases to be visible. This might easily be imagined to cause some important change in the nature of the results. Thus it was judged of importance to obtain a series independent of background effects.

FIG. 10.



The simplest "dead black" background is the mouth of a black box into which a beam of narrow aperture may be passed, provided that it does not illuminate a visible part of the interior. The apparatus employed was arranged in this manner and the illumination so controlled that when a disc was held (by means of a very fine blackened iron wire) in the beam it simply shone out from surrounding darkness. Distances at which it became invisible were taken. Results were now obtained by observers B and F with this arrangement. (*See* Table 6 and Diagram 7.)

FIG. 7.



The results of the two observers are plotted in the diagram. They show that the effect of the change of object is no longer to produce a break in the results. Outstanding errors appear accidental. The change of slope (from 2 to 1 in this case) is quite as well marked as before. The break, then, noted by observers shows that with a larger illuminated field the visibility of the disc improves. This result does not appear to teach anything regarding the improvement in sensitiveness of the fovea *only*, as all of the observers worked consistently with averted vision.

Effect of Area of Background.—In order directly to test the influence of the size of background on the light necessary

to perceive the test-object a series of measurements was made in which the aperture of the beam was reduced by means of an iris diaphragm. The effect of this was to cut down the circle of illumination on the background of black velvet. The diameter of the circle was measured in each case, the observer remaining at a constant distance. Results by A, B and E are given in Table 7. Each figure is the mean of many separate observations.

It should be remembered that at the point where the disc ceases to be *distinguishable* from the background it may be sending quite a measureable quantity of light to the eye, and might be seen easily if the background were not present. It is generally much easier to perceive an object when it alone is visible, than when it appears against another surface of lesser brightness.

These results were confirmed by observer E, who worked with an apparatus modified to admit of a larger subtense of background. Two kinds of velvet were employed as background; in the second case the reflected light from the velvet could scarcely be seen after twenty minutes in darkness. It is sufficient, however, to cause a decided change in the visibility of the test-object seen against it. Several readings were taken by E on the same object against a " dead black " background.

Effect of Light-adaptation of the Eyes.

From certain features of the performance of telescopes to be described it was thought that the adaptation of the eyes to a faint light might considerably affect this action.

In order to test this point, the experiments on a series of square discs were repeated, with the difference that the objects were viewed through an aperture in a large piece of white card dimly illuminated from the back of the room. The eyes were adapted to this intensity of light by gazing at the surface when not making readings. The method adopted was to reduce the intensity of light by means of the annulus until the disc did not appear till about three seconds after looking away from the surface and through the aperture.

Results are exactly corresponding to those of Table 5, except that the eyes were light-adapted. (*See* Table 8 and Diagrams 8, 9 and 10.)

The results of observers B and C are curious in that they indicate that less light on the disc may be required while looking through the aperture in the cardboard screen when the eyes are adapted to an illumination approximately equal to that of the background (and moreover are receiving a certain amount of light which illuminates the peripheral parts of the retina) than when no screen is present. This effect is evidently connected with the results obtained by varying the size of the background. It was found by B and C independently that the phenomenon can be observed directly, and is most striking

when the illuminated screen is arranged to match the background in brightness and to appear continuous with it.

When this has been done the light is cut down on object, background and screen till the disc can barely be seen. On turning off the illumination of the screen the disc entirely disappears, but comes into view again almost directly after the screen is again lit up.

The effect was confirmed by B and C, who made careful threshold readings in both circumstances after waiting some time in order practically to complete the adaptation in each case. (*See* Table 9.)

As a further test on this point observer B took readings with a series of discs, the illumination of the screen being cut off while the disc was observed. The eyes were kept light-adapted by looking at the screen for three seconds, then at the disc for not more than three seconds, and so on. Under these circumstances the *slope* of the "line" representing the observations is nearer to the original slope for dark-adapted eyes.

Two possible explanations of the effect suggested themselves. Firstly, the retina may be somewhat similar in action to a photographic plate, a certain amount of light energy being needed to produce the initial impression; a small increase can then produce a relatively large action. Secondly, the effect may be due to a species of glare. In trying to view the object against a small relatively bright background certain parts of the retina which were in darkness suddenly receive light, owing to the motion of the eye. This results in a temporary dazzling effect and the small object becomes invisible. On the other hand, if most of the retina is adapted to the required order of brightness no dazzling can occur.

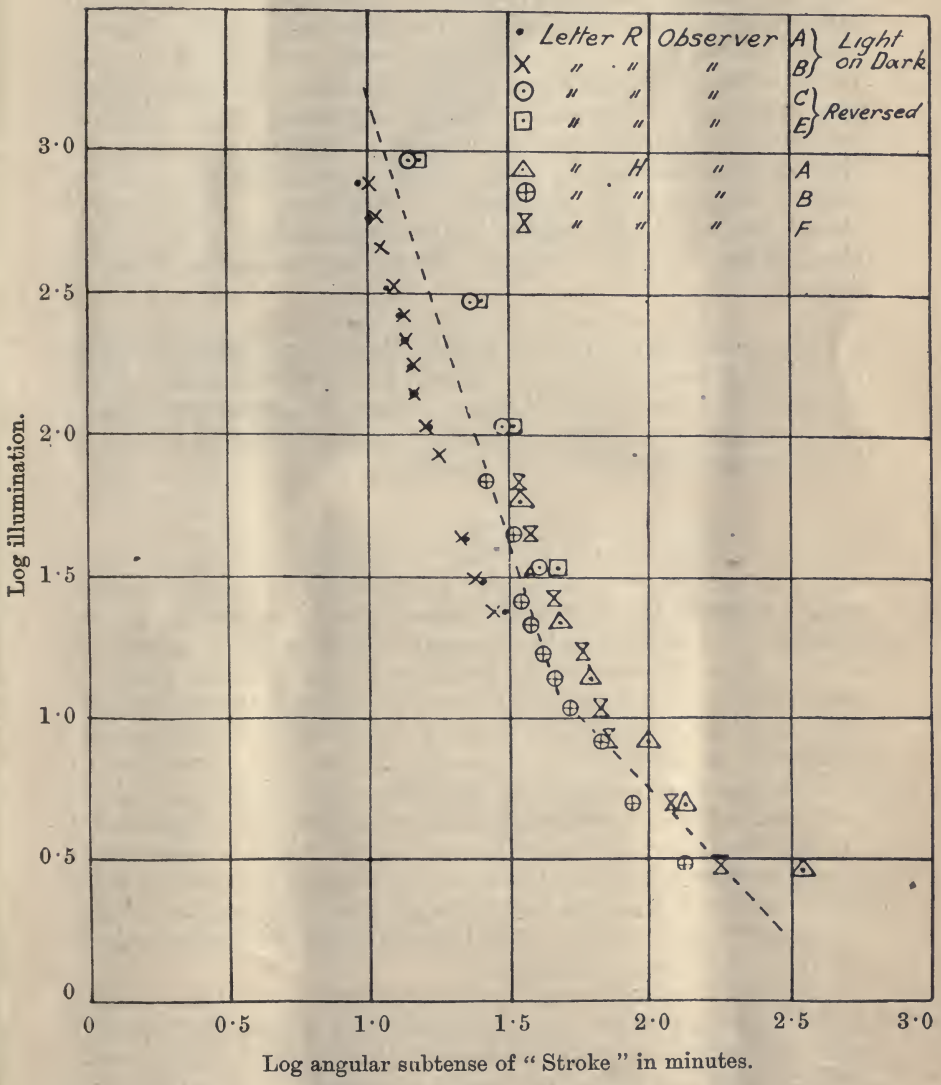
It has been frequently stated that for greatest comfort in observation the whole of the retina should be illuminated fairly uniformly. This, then, applies to even the smallest light-intensities, and would appear to be important in relation to night-vision, as the results of observer E show that, by increasing the subtense of the background from 12° to 27°, a small disc could be seen with half the original intensity of illumination.

The first explanation above appears somewhat unlikely, as it has been shown that the presence of any illuminated field, is prejudicial to the seeing of the disc. The second appears to fit the facts more nearly. Notice that when the background, which is dimly lighted in relation to the test-object, becomes comparatively small, the tendency noticed with all test-objects sets in; namely, that it is perceived as a blurr of light, brighter in the centre, and fading off towards the edges. Also, the apparent loss of definition, and the uncertainty of accommodation, add to the difficulty of perceiving the disc as a separate object. Such considerations, however, hardly apply to backgrounds 12°–30° in subtense, and the advantage derived by an increase in

such cases seems probably due to the dazzling effect to which reference was made.

Visibility of other Objects (*Letter Tests*).—It was now judged of importance to extend the investigations to other objects. The ability to read letters is a test of visual acuity, but different letters cannot well be used in critical work of this type. Trained observers can, however, estimate very consistently the amount of illumination they require to read a particular letter.

FIG. 11.



First readings were taken with a letter *R* cut from the same black paper from which the squares were made, and second readings with a letter *H* of larger thickness of stroke. (*See* Table 10 and Diagram 11).

Indications from Experiments on Test Letters.

Results by A and B on letter R, were markedly different from those on letter R, reversed so as to show dark on light. In the latter case, however, a small bright background for the dark letter was in contrast to the rest of the dark velvet main background, so that doubtless the quantity of light required cannot be considered comparable in the two cases. Moreover, different observers are apt to adopt a very different standard in estimating the light required, to be sure of the letter. Hence, these results should not be interpreted as indicating the relative disability of a light on dark or dark on light contrast for lettering or figures. This is obviously an important subject, and further work may be undertaken in this and similar connections. In both sets of results, the slope of the line is important for the present investigation. We see that the subtense of the stroke is the determining factor. This changes from nearly 3 to about 1 at a subtense of about 50 or 60 minutes.

The causes of the various effects which have been described are almost certainly physiological and psychological. They suggest that certain numbers of retinal elements are capable of acting in conjunction. The discussion of these points is, however, outside the scope of this paper.

Effect of Aberrations of the Eye.

It is important to recognise that the loss of acuity in darkness is almost entirely a retinal effect, and is not due to optical defects. In stronger light, however, the increase of acuity on cutting down the area of the pupil employed is well marked in many persons; this leads to the conclusion that in daylight the use of a small exit-pupil may be a considerable advantage. According to Tscherning, however, the state of correction in the human eye varies from one person to another and it is improbable that a satisfactory compensation could be given by an instrument. In order to determine whether aberration would be likely to cause trouble in practice experiments were made by A and B on the large letter *B* of a Snellen chart, using "orthoptic" spectacles, in which a small iris diaphragm is held in front of the pupil of one eye.

The illumination on the chart was varied by the annulus till the letter became unrecognisable. If spherical and other aberrations have a negligible effect the product (light intensity) × (area of diaphragm) should be constant. (*See* Table 11.)

Undoubtedly the results of A and B are both affected by small amounts of astigmatism present in the eye. The total illumination of the retinal image required is, however, very nearly constant within the limits of error to be expected. Certain persistent irregularities were observed for the diameters larger than ·5 cm., which tend to show that in increasing the exit-pupil of an instrument beyond this diameter any improvement in *acuity* resulting from the increased light is uncertain. Thus observer B very persistently required more light with aperture ·64 than with aperture ·62. This may be due to an irregularity just missed by the smaller aperture.

It should be remembered that for the reading of this letter, subtending 19 minutes in breadth of stroke, a fair amount of light is required. The presence of the letter could be recognised at much lower intensities, but its form could not be distinguished. In connection with the question of aberration the work of Gullstrand may be remembered, in which it is shown that, owing to the variation of refractive index of the crystalline lens, the eye is spherically corrected (in many subjects) for a ring of 4 mm. radius from the centre of the pupil. Chromatic aberration is uncorrected, but the loss in acuity from this cause is not of the order which could explain the observed effects. Lord Rayleigh ("Camb. Phil. Soc. Proc.," IV., p. 4, 1883) states that he was short-sighted in darkness, and that the use of spectacles projecting the images of objects to distances of less than three feet rendered visibility considerably better. The invisibility did not do away with the differences between large and small objects. This suggests that in darkness the eye tends to seek the position or accommodation of rest when no distinctly defined objects can be seen. The case would appear to be exceptional.

As regards his suggestion that aberration is responsible for the outstanding differences between large and small objects, the magnitude of the effects would appear to negative this. Discs subtending 20 to 30 minutes at the threshold of vision lose their shape and may appear as a small blur of light much smaller than the object itself. Nevertheless faint stars under similar conditions appear perfectly defined as points of light. The eye can resolve stars separated by 3 or 4 minutes of arc.

It would be a good precaution for a user of night-glasses with a large exit-pupil, after having focussed carefully in the daytime, to observe a bright star. Any considerable aberration should certainly be detected, but probably the amount present will not be sufficient to spoil the performance of the glass on ordinary objects. No such deterioration can be detected by the present writer.

Summary of Results.

Naked Eye Tests.

(1) For objects seen by contrast against a faintly illuminated background, and subtending angles between

1 minute and 1 degree approximately, the light necessary to recognise them is proportional inversely to a power of their smallest angular subtense, generally between 2 and 3. For objects larger than 1 degree approximately the light necessary is inversely proportional to the angular subtense. For a dead black background the power in question is 2 for objects subtending angles between 1 minute and 1 degree.

(2) The illuminated background should be made as large as possible for best seeing.

(3) The eyes should be adapted to an illumination not stronger than that of the background.

(4) Aberrations of the eye are not responsible for loss of definition in darkness.

The following deductions may be made as to the behaviour of telescopes:—

(1) Advantage will be secured in all cases where magnification can be increased without diminishing the brightness of the image.

(2) Advantage after this point will still generally be secured for objects subtending angles between 1 and 60 minutes in the field of view of the instrument, but when the latter condition is reached the performance will fall off.

(3) The apparent field of view should be made as large as possible.

(4) Every care should be taken to screen the eyes from all light brighter than that in the field of view.

These conclusions, with certain limitations, have all been verified in practice.

Direct Tests with Telescopes.

It is important to confirm practically the deductions made from the foregoing experiments as to the performance of telescopes. For preliminary tests a series of eyepieces was employed which, while using a common objective, varied the magnification from 2 to 25. Certain other complete instruments have been used for purposes of comparison, notably a small astronomical telescope and a Galilean binocular. Tests are made first by using each system in succession on a series of critical objects in a faint light. Secondly, by varying the illumination so as to determine the "threshold" value for each instrument when used on some standard object. The latter method is quantitative and yields more certain results.

The main difficulties in work of this kind are met with in all "night-glass" work. The exit-pupil is rather hard to find in the darkness and a support for the head, or a rubber eyepiece cap, is an advantage. It is practically impossible also to focus a telescope satisfactorily at these low illuminations. This must

be done carefully with an eye at rest in a brighter light. If then the eye is allowed to relax in darkness the observer is sure of a perfect focus. Any strain or uncertainty of accommodation tends to prevent efficient use of the telescope. Even after considerable practice it is difficult to avoid eye-strain and consequently each series of observations must be comparatively short.

The following particulars may be given of the simple tests on critical objects, which were carried out in fading daylight in one of the corridors of the Imperial College :—

Objects.—A series of circular white discs, diameters, 15, 10, 5, 2 and 1 cms., called A B C D E respectively. Pointer, black, width 0·6 cm. on each disc. Discs mounted on brown cardboard. Distance of objects from telescope, 68·5 metres. Approximate angular subtense of A, B, C, D, E = 7 5, 5, 2·5, 1, 0·5 minutes respectively. The method adopted was to use each system in rotation and to note how many discs could be seen, also on how many of these the pointer could be seen. Tests were made by A and B; typical results for observer B are quoted as a specimen of the series. (*See* Table 12.)

The following conclusions were deduced as the result of the complete series of observations made in this manner .—

(1) Where magnification can be increased without diminishing the luminosity of the image, a great advantage is derived in all cases except where the object fills too great a proportion of the field of view.

(2) When the luminosity *is* diminished advantage is still gained, especially on objects of which the images subtend angles of less than a few minutes. On images subtending angles near one degree, however, increasing magnification gives poorer results if the light is cut down.

On the larger objects, the Galilean binocular was very good owing to the brilliancy of the image. It was found that on the pointers the performance of the system (magnification = 12, relative luminosity = ·05) gave better results. The performance of the large telescope (m. = 50) was in all cases much better than any of the others, and objects which could not be detected with the binocular were easily visible with this glass. It should be recorded that the binocular is *apparently* far more satisfactory to use in a faint light, but careful observation shows that the performance is really not so good as that of larger instruments.

Threshold Tests with Telescopes on Standard Objects.

In order to permit of work in a comparatively small darkened room, an auxiliary 3″ astronomical telescope was used as a collimator, the small image of the object produced by the eyepiece being projected to "infinity" by the O.G. through which it was viewed by means of the experimental systems.

In order to determine the subtense of the images, the "magnification" of the collimator was found by employing a known object with a telescope and divided circle.

The subtense of an image could then be calculated from the dimensions of the object and the magnification of the auxiliary system.

With the apparatus described above, "threshold" experiments were carried out employing a disc of black paper on the black velvet background. The annulus was employed to reduce the illumination till the disc could no longer be perceived with each system in succession. Focussing was done by an assistant. Series of results were repeated in the reverse order. (*See* Table 13.)

These results clearly show that the performance of increasing magnification (when the exit-pupil is already smaller than that of the eye) becomes rapidly worse on objects subtending angles greater than one degree in the field of view. This was anticipated from the naked eye tests. In order to test resolving power, an object was constructed of black and white paper to form a "grating," having spaces of increasing width. When this was viewed through the optical system, the illumination could be diminished till it was impossible just to resolve the grating elements at some particular point. A rotating sector was used to vary the light, and readings were taken with each magnification, care being taken to eliminate as far as possible effects due to varying adaptation. In this case, the eyes were kept in complete darkness except for the light from the image. In all cases the illumination is diminished by the telescope proportionately to the inverse square of the magnification. (*See* Table 14.) Observer A has a tendency to require more light with the higher magnifications, but with B and C the reverse is true; visibility improves with increasing magnification, although this entails reduction of the light.

Further tests were made with the same apparatus in which black letters on white cardboard were used as critical objects. The results are tabulated and the angular subtense of the width of the stroke is given against the sector aperture required in order to read the latter. Each figure is the mean of several results (*see* Table 15).

The performance of the higher powers appears to be rather better.

Light-Adaptation.—If the eyes are somewhat light-adapted a change in the performance of the different magnifications may be expected from the indications of the naked eye tests. In a further series of experiments on the same test letters as were previously employed the eyepiece of the telescope passed through a sheet of white card very dimly illuminated, to approximately the same order of brightness as used in the naked eye experiments.

Tests were made both by sector and annulus (in the case of the annulus equivalent, sector values are tabulated) (*see* Table 16).

In this case A and C agree in finding the higher magnifications a disadvantage. The illumination of the field of view is lower than that of the card, to the brightness of which the eye is adapted with the higher magnifications. This explains the falling off in the performance of these powers found by A and C. The reason for the constancy of results by observer B is not clear.

The inferior results given by the higher powers were also noticed in a series of preliminary experiments carried out in a dim light. The object was a graduated test chart and the illumination was controlled by the distance of a lamp.

Considerably less light was needed with the lower magnifications. It appears clear that in order to use high powers with advantage the eye should be adapted to total darkness, or to an intensity of illumination in no case exceeding that of the field of view.

Field Tests.—In addition to the quantitative experiments which have been made in the manner described, considerable time has been spent at night in comparing the performances of various types of telescopes in the field under differing conditions. Among the instruments employed were :—

	Magnification.	Exit-Pupil. mm.	Apparent Field.
(1) Galilean binocular - - - -	3½	—	15°
(2) Experimental telescope (with erecting roof prism).	6	8	30°
(3) Ordinary day prism binocular - -	6	4	45°
(4) Zeiss prism night-glass binocular - -	7	7·5	40°
(5) Experimental telescope with erecting roof prism.	8	6	30°
(6) Astronomical telescope, 2½-inch O.G., prism erector.	22	2·5	30°
Do. with 4-lens erector - - -	34	1·65	25°

The following conclusions were reached :—

(1) Considerations limiting the useful increase or magnification for day use with hand binoculars are even more important for night work. For hand use alone a magnification of 7 is a little high.

(2) Where some definite small object is to be observed and where a stand for the instrument is to be employed (in flag signalling, &c.) magnification may be usefully taken higher, according to the amount of light available. [It may be remarked that for

lamp Morse signalling at great distances practically the only consideration is the diameter of the object-glass. [A high magnification is useful to reduce the luminosity of the surrounding field. As many glass air-surfaces should be eliminated as possible. There seems no reason why an ordinary inverting astronomical telescope with a small erecting finder should not be used. With reference to flag or semaphore "flicker," experiments have shown that the growth of visual impressions of contrast is much slower at low illuminations. Therefore a certain "brightness" must be maintained for fast signalling.]

(3) Binocular instruments are very desirable for comfort.

(4) The large apparent field of view of the Zeiss binocular confers an immense advantage in "confidence" and ease of observation.

(5) Since for hand use low magnifications are employed the exit-pupil should be 7 or 8 mm.

(6) The magnification that can be used with advantage varies greatly with the amount of light available. When the night is very dark, only comparatively large objects are generally perceptible and the use of glasses in this case is of little value, especially if the objects viewed subtend too large an angle in the field of view. Smaller objects may, however, be seen against the sky, and a larger magnification is then useful. For general purposes the power should not be too high, probably 5 or 6 would be as useful as any for a hand instrument.

(7) Diffuse light in the images arising from "ghosts" and filmed surfaces is an enormous drawback, especially when working at dusk with a sky much brighter than the objects viewed. Certain instruments appear very liable to this effect and tests have been made on this point.*

Final Deductions.—The conclusions to which the naked eye tests pointed (p. 24) have thus been verified in practice, with the reservation that a steady instrument is employed. Nothing but experience can determine the best compromise in a hand instrument, and it is believed, from the results of many tests, that a power of 5 or 6, with the largest field of view possible and an exit-pupil of 7 or 8 mm., will be the best instrument for night use. In some cases instruments may be required for use on objects of very large subtenses when lower powers may be used.

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* *The Optician*, August 2nd, 1918.

For stand instruments we are not so limited. Suppose it were required to view an object, say a man's face against a darker background, in width about 6 inches at 100 yards, or a figure of a man against the skyline, say 2 feet at 400 yards: these subtend 5·6 minutes at the eye. To obtain best results in a faint light we use a power of 10, bringing their subtense up to 1 degree. An exit pupil of 8 mm. would mean the use of an 80 mm. O.G., which is easily attainable. A greater magnifying power might be used if it were possible to increase the O.G. diameter further, but not unless. However, for objects subtending lesser angles, the magnification may still be increased till they subtend nearly one degree, even though this entails the loss of light.

Practical work with high magnification systems has confirmed the advantage for particular cases of such instruments, but two points especially have to be borne in mind. Firstly, if the exit-pupil is small the luminosity of the field of view may be far less than that of the surroundings of the observer, and the work of this paper suggests, while practical experience emphatically confirms, the great importance of protecting the eyes from all brighter illumination, especially the sky. The second difficulty (mentioned above), which is very pronounced in practical use, is that of stray light in the field of view. It is especially met with when working at dusk while the sky is still moderately bright. If the exit-pupil is small the brightness of the stray light seriously competes with that of the image. It arises from "ghosts," reflections from the walls of the instrument, filmed surface, and other causes. If present it may be fatal to the successful use of the instrument. Bearing in mind the wide range of subjects for a night-glass it would be a decided advantage to be able to vary the magnification in several steps, say, 10, 20, 30. As far as present experience goes it would seem advisable not to take magnification much higher when using an 80 mm. O.G., unless stray light can be more effectively eliminated. It must be clearly remembered, however, that high powers are not recommended for a general survey of the landscape, but merely for the observation of particular small objects.

These conclusions point to the utility for night work of stand telescopes in artillery O.P.s and elsewhere for such work as observing shell bursts in the dusk, etc.

For economy in space and to save glass-air surfaces, a cemented prism-erecting system should be employed.

In conclusion I must express my sincere thanks to all the observers, and especially to Professor F. J. Cheshire, C.B.E., and Professor A. E. Conrady, for their interest and helpful advice.

TABLE 1.

	cms.		cms.
Breadth of 1st pointer	= 0·169,	of 2nd pointer	= 0·09.
Diameter of „	= 2·0	of 2nd dial	= 1·0.
Focal length of O.G.	= 23		
Aperture „ „	= 2·7.		

Data of Systems.

Magnification of Telescope System.	Diameter of Exit-Pupil.	Relative Luminosity of Image.
1 (naked eye) - -	—	1
2 - - -	>10 mm.	0·8
4·9 - - -	5·5 „	·35
6·0 - - -	4·5 „	·22
9·3 - - -	2·9 „	·103
12·5 - - -	2·2 „	·053
25·6 - - -	1·0 „	·011

Experimental Results.

Magnification.	Mean Sector Aperture required.	"Probable Error" of Sector Value.	Effective Illumination of Image.	Angular Subtense of Image of Pointer (minutes).
1 (naked eye)	Could not be seen with maximum illumination (Sector 50).			
2 - -	41	3·0	1·7	0·7
4·9 - -	11	1·0	0·2	1·7
6·0 - -	11	0·9	0·13	2·1
9·3 - -	10	0·8	0·054	3·3
12·5 - -	11	0·6	0·030	4·4
25·6 - -	11	1·0	0·006	9·0
1 - -	Indistinguishable.	—	—	—
2 - -	„	—	—	—
4·9 - -	47	1·3	0·86	0·92
6·0 - -	26	1·6	0·30	1·12
9·3 - -	20	0·7	0·11	1·74
12·5 - -	20	0·5	0·055	2·34
25·6 - -	15	1·0	0·009	4·8

TABLE 2.

Angular Subtense of Pointer.			Effective Illumination.
Observer A.	Observer B.	Observer C.	
2·6	2·9	3·6	·052
1·9	1·55	2·3	·104
2·3	1·45	1·55	·156
1·35	1·05	1·03	·26
1·2	0·93	0·81	·52
0·97	0·83	0·73	1·04
0·73	0·63	0·61	1·56
0·64	0·63	—	2·08

TABLE 3.

Naked Eye Experiments.

Object—Disc of White Card on Black Velvet; diameter, 1·55 cms.

Log Illumination.*	Log Subtense in Minutes.		
	Observer B.	Observer C.	Observer D.
2·5821	·5963	·6852	·6661
·5063	·5963	·7489	·8235
·3842	·6813	·7581	·8128
·2723	·6127	·6474	·7266
·1549	·6852	·7054	·8345
·0592	·6972	·8235	·9862
1·9623	·7921	·8235	·9862
·8699	·7871	·8235	1·0276
·7637	·8128	·8815	1·0734
·6540	·8458	·9707	1·0931
·5459	·8693	·9342	1·1825
·4272	·9484	·9862	1·2215
·3145	·9484	1·0106	1·2952
·1991	1·0106	1·0734	1·2952
·10841	1·0545	1·1034	1·5225
·0134	1·1584	1·2491	1·7226

* Log Illumination 2 = ·05 m.c.

TABLE 4.

Naked Eye Experiments.

Varying Distance.

Observer A.

Log. Illumination.*	Log. Subtense.	L.I.	L.S.	L.I.	L.S.
	1*st Disc.*		2*nd Disc.*		3*rd Disc—continued.*
3·6232	·6565	2·9615	·9604	·6540	·5466
·5011	·7017	·7630	1·0048	·5459	·6016
·3892	·7463	·5343	1·0496	·4272	·6383
·2718	·7767	·3417	1·1103	·3145	·6927
·1761	·8000	·1433	1·1683	·1991	·7719
·0792	·8447	1·9253	1·2500	·1084	·8910.
2·9868	·8913	·6939	1·4114	·0445	·9523
·8808	·9343	·3928	1·4949	·0134	·9937
·7709	·9721				
·6628	1·0027		3*rd Disc.*		4*th Disc.*
·4314	·0715	2·0592	1·3916	0·9174	1·9342
·1303	·2006	1·9623	·4294	·6906	2·1213
		·8699	·4622	·4625	·3902
		·7639	·5263	·3079	·5985

Observer B.

L.I.*	L.S.	L.I.	L.S.	L.I.	L.S.
	1*st Disc.*		2*nd Disc.*		3*rd Disc.*
3·6232	·6069	2·8857	·8799	1·8699	1·4294
·5011	·7234	·7636	·8929	·7639	·4977
·3892	·7582	·6517	·9271	·6540	·5466
·2718	·7830	·5343	·9565	·5459	·5900
·1761	·8094	·4386	·9760	·4272	·6135
·0792	·8231	·3417	1·0006	·3145	·6784
2·9868	·8521	·2493	1·0267	·1991	·7548
·8808	·8831	·1433	1·0544	·1084	·8476
·7709	·8995	·0334	1·0689	·0445	·9268
·6628	·9343	1·9253	1·1501		
·4314	·9923	·8666	1·1746	4*th Disc.*	
·1303	1·0592			0·9174	1·9096
				·6906	2·0312
				·4625	·2141
				·3079	·4114

TABLE 4—*continued.*

Log Illumination.*	Log Subtense.		Log Illumination.	Log Subtense.	
	Observer C.	Observer E.		Observer C.	Observer E.
1st Disc.			*2nd Disc*—continued.		
2·9615	0·9527	·9681	·3145	·5821	·5725
·4852	1·0592	1·1103	·1084	·6498	·6442
·0334	1·1939	1·2210	·0134	·6912	·6912
1·5297	1·3145	1·3145			
2nd Disc.			*3rd Disc.*		
			0·9174	1·7277	1·7624
1·9623	1·3996	1·4291	·6906	1·8874	1·8594
·7639	·4949	·4571	·4625	2·1982	2·0492
·5459	·5363	·4681	·3079	2·1982	2·1013

* Log illumination 2 = ·05 m.c.

TABLE 5.

NAKED EYE EXPERIMENTS.

(Constant Distance.)

Log Subtense in Minutes.	Log Illumination.†			
	A.	B.	C.	D.
1·1049	2·9912	2·9191	3·4183	2·9868
1·4059	2·3711	2·1903	2·5211	2·4579
1·5820	1·8831	1·6198	2·1903	2·0134
1·7070	1·5821	1·3696	1·7582	1·8469
1·8039	1·4742	1·1909	1·7464	1·7092
1·8831	1·4016	1·1830	1·4675	1·4513
1·9500	1·3145	1·0958	—	—
2·0080	1·2353	0·9552	1·3217	—
2·1049	1·0445	0·9343	1·2063	—
2·1841	0·9165	0·7292	1·1456	—
2·3090	—	0·6591	0·9781	—

† Log illumination 2 = ·015 m.c.

TABLE 6.

Naked Eye Experiments.

(Dead black background.)

Log Illumination.†	Log Subtense.		Log Illumination.	Observer B.	Observer F.
	Observer B.	Observer F.			
2·9615	—	·6835	1·1333	1·5100	1·6541
·7097	·6612	·8596	0·9174	1·6401	1·8330
·4852	·8266	·9740	0·4137	2·0970	—
·0334	·9275	1·1890	0·5928	1·8162	1·9537
1·5297	1·1384	1·4394	0·5144	1·9480	2·1607
1·5357	1·2933	1·5363	0·2785	2·1241	2·5016
1·4183	1·3602	1·5363	0·0626	2·4394	—

† Log illumination 2 = ·05 m.c.

TABLE 7.

Effect of Size of Background.

Subtense of Object-disc of black Paper = 13 Minutes.			
Observer A.		Observer B.	
Subtense of Background in Degrees.	Relative Illumination required.	Subtense of Background in Degrees.	Relative Illumination required.
11	10	10·5	9
9	16	7	10
6·5	17	5	13
4	20	4	16
3·4	28	1	39

Results of Observer E.

Subtense of Object-disc of black Paper = 1 Degree.		
Nature of Background.	Angular Subtense of Background in Degrees.	Relative Illumination required.
Lighter velvet - -	6·3	20
	27	9
Darker velvet - -	6·3	11
	12·2	7·5
	27	3·7
Dead black - -	—	3·1

TABLE 8.

Log Subtense in Minutes.	Log Illumination required.*					
	Observer A.		Observer B.			Observer C.
	(1)	(2)	(1)	(2)	(3)†	
1·1049	3·2718	3·3424	2·9031	2·8129	2·8865	3·1038
1·4059	2·7324	2·6812	2·3802	2·0745	2·1761	2·5056
1·5820	2·2175	2·1903	2·1303	1·8699	1·8959	2·3385
1·7070	2·1139	1·9476	1·7752	1·6390	1·5643	1·9695
1·8039	1·7752	1·7219	1·7639	1·4272	1·4513	1·9084
1·8831	1·6390	1·5991	1·6613	1·2542	1·8831	1·8125
1·9500	1·5166	—	1·4629	—	—	—
2·0080	1·5063	—	1·4513	—	—	1·5991
2·1049	1·3455	—	1·3674	—	—	1·5733
2·1841	1·2723	—	1·2810	—	—	1·4629
2·3090	1·1549	—	1·2255	—	—	1·3882

* Log illumination 2 = ·015 m.c.
† Illumination on screen removed while observing disc.

TABLE 9.

Data.—Subtense of disc at eye (about) = 20′.
,, background seen through aperture = 3°.
,, surface of screen = 45°.

Illumination of screen adjusted so as not to exceed that of the background when the disc is just visible.

Light required to perceive Disc.

Observer B.				Observer C.			
Screen not Illuminated.		Screen Illuminated.		Screen not Illuminated.		Screen Illuminated.	
Annulus Readings.	Mean Equivalent "Sector" Value.	Annulus Readings.	Mean Equivalent "Sector" Value.	Annulus Readings.	Mean Equivalent "Sector" Value.	Annulus Readings.	Mean Equivalent "Sector" Value.
70	17·5	115	9·2	70	17·7	90	13·5
115		150		97		106	
85		155		77		120	
75		155		95		125	

TABLE 10.

Letter R (cut from black paper). Breadth of Stroke = 1·9 cms. Background: Black velvet.

Log Illumination.*	Log Subtense of Stroke.	
	Observer A.	Observer B.
2·8857	0·9700	1·0022
2·7636	1·0055	1·0192
2·6517	1·0406	1·0442
2·5343	1·0669	1·0827
2·4386	1·1033	1·1161
2·3417	1·1249	1·1249
2·2493	1·1430	1·1430
2·1433	1·1766	1·1571
2·0334	1·2240	1·1867
1·9253	1·2528	1·2296
1·6939	1·3308	1·2901
1·4878	1·4086	1·3679
1·4239	1·4349	1·4359
1·3928	1·4826	1·4349

Letter R (dark on a light ground of small dimensions). Breadth of Stroke = 1·9 cms.

Log Illumination.	Log Subtense of Stroke.	
	Observer C.	Observer E.
2·9615	1·1698	1·1471
2·4852	1·3530	1·3675
2·0334	1·4851	1·5049
1·5297	1·6069	1·6612

Letter H. Breadth of Stroke = 5·08 cms. Light on dark ground.

Log Illuminat·on.	Log Subtense of Stroke.	
	Observer A.	Observer B.
1·7697	1·4788	1·5432
1·5357	1·5389	1·5890
1·3226	1·6037	1·6682
1·1333	1·7107	1·7950
0·9174	1·8711	1·9869
0·6906	1·9869	2·1119
0·4625	2·1630	2·5432

Same Object.

Log Illumination.	Observer B (repeated).	Observer F.
1·8455	1·4293	1·5346
·6476	1·5098	1·5701
·4183	1·5432	1·6511
·3226	1·5890	1·6740
·2257	1·6190	1·7508
·1333	1·6624	1·7651
·0273	1·7113	1·8157
·9174	1·8108	1·8112
·6906	1·9200	2·0749
·4625	2·1119	2·2210

* Log illumination 2 = ·05 m.c.

TABLE 11.

Acuity and Size of Pupil of Eye Employed.

(Low illuminations.)

Subtense of "stroke" of test letters = 19 minutes.

I = Illumination on chart required to read test letters.
D = Diameter of aperture in cms.

D.	Observer A.		Observer B.	
	Log I.	Log ($I \times D^2$).	Log I.	Log $I \times D^2$.
·075	3·4955	1·2457	3·4742	1·0444
·175	2·3927	0·8787	3·5185	1·0045
·320	1·8940	0·9542	1·9891	0·9993
·445	1·5818	0·8786	1·7422	1·0390
·555	1·4678	0·9564	1·6467	1·1353
·625	1·5312	1·1230	1·4780	1·0698
·640	1·3631	0·9755	1·5435	1·1559
Naked eye	1·3760		1·4920	

TABLE 12.

Telescope Tests.

(Typical results only.)

Observer B.

Magnification.	Diameter of Exit-Pupil.	Relative Brightness of Image.	1st Series (smallest).		2nd Series (less light).	
			Disc seen	Pointer seen on.	Discs seen	Pointer on.
1 naked eye	—	1·0	C.	A.	none	none
2 - -	>10 mm.	0·8	D.	B.	A.	„
4·9 - -	5·5	0·35	D.	C.	B.	„
6·0 - -	4·5	0·22	D.	C.	C.	A.
9·3 - -	2·9	0·10	E.	D.	C.	A.
12·8 - -	2·2	0·05	E.	D.	C.	A.
25·6 - -	1·0	0·01	E.	D.	B.	A.
53 astro-telescope	1·0	0·01	E.	D.	D.	C.
5·5 Galilean binocular.	>10 mm.	0·08	D.	C.	C.	A.

* Assuming pupil of eye = 8 mm. and allowing for reflection.

TABLE 13.

Magnification.	Exit-Pupil.	Subtense of Disc in Field of View.	Equivalent Sector Values of Light necessary to Perceive the Disc.	
			Observer A.	Observer B.
4·9	5·5 mm.	1° 26	4·5	2·6
9·3	2·9 „	2° 44	4·0	5·0
15·4	1·75 „	4° 31	7·8	10·4
33	0·82 „	9° 41	13·0	12·0

TABLE 14.

TESTS ON THE ILLUMINATION NECESSARY WITH VARYING MAGNIFICATION TO RESOLVE A GIVEN OBJECT.

The "angle" is that subtended by the critical grating element in the field of view.

Observer A.

Magnification.	Angle in Minutes.	Mean Sector.	Angle.	Mean Sector.	Angle.	Mean Sector.
12·8	9·3	23	16	11	6	24
15·4	11	20	21	18	7	30
18·4	13	27	24	13	8	37
25·6	19	34	34	16	11	35
33·0	24	39	43	13	15	33

Observer B.

Magnification.	Angle.	Mean Sector Reading.		Angle.	Mean Sector Reading.	
		Right Eye.	Left Eye.		Right Eye.	Left Eye.
12·8	16	10	14	6	27	24
15·4	21	8	7	7	15	19
18·4	24	7	8	8	16	14
25·6	34	7	6	11	18	15
33·0	43	7	9	15	16	16

Observer C.

12·8	9·3	14	15	16·0	14	19
15·4	11·5	12	12	20·8	15	17
18·4	13·4	14	14	24·3	17	16
25·6	18·6	15	15	33·7	14	17
33·0	24·0	8	8	43·5	18	14

TABLE 15.

Light required to read Test Letters with Telescopes.

DARK-ADAPTED EYES.

1st tests (with annulus).

Magnification.	Subtense of Stroke in Minutes.	Equivalent Sector Values.		
		Observer A.	Observer B.	Observer C.
4·9	2·7	27	32	—
6·0	3·3	26	31	—
12·8	16·9	28	29	—
33	19	23	24	—

2nd tests with sector (different lettering).

12·8	17	17	19	19
15·4	22	18	14	18
18·4	25	17	16	19
25·6	34	19	17	18
93	45	18	16	14

TABLE 16.

Light required to read Test Letters with Telescopes.

LIGHT-ADAPTED EYES.

Magnification.	Subtense of Stroke.	A.			B.			C.	
		Right Eye.	Left Eye.	Right with Annulus.	Right Eye.	Left Eye.	Right with Annulus.	Right Eye.	Left Eye.
12·8	17	25	25	25	22	18	12	25	25
15·4	22	24	20	29	15	18	12	27	26
18·4	25	23	24	35	16	16	10	24	24
25·6	34	28	30	37	21	22	9	36	32
33·0	45	35	35	39	20	24	12	41	35

Continued from page ii *of cover.*]

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Food Investigation Board. Report of the Engineering Committee on the Design of Railway Wagons for the Carriage of Perishable Foods. (1919.) Price 3*d.* (by post 4½*d.*).

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Research Association 1. (*Revised.*) The Government Scheme for Industrial Research.

Research Association 2. (*Revised.*) Draft Memorandum and Articles of Association for Research Associations.

Research Association 3. (*Revised.*) Conditions as to the Payment to Research Associations by the Committee of Council.

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